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Understanding the Roles of the Strategic Element Cobalt in Nickel Base Superalloys

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UNDERSTANDING THE ROLES OF THE STRATEGIC ELEMENT COBALT IN NICKEL BASE SUPERALLOYS

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SUMMARY

The United States imports over 90 percent of its cobalt, chromium, tantalum and columbium -- all key elements in high temperature nickel-base superalloys for aircraft gas turbine disks and airfoils. NASA, through joint government/industry/university teams, has undertaken a long-range research program (COSAM - Conservation of Strategic Aerospace Materials) aimed at reducing or eliminating these strategic elements by examining their basic roles in superalloys and identifying viable substitutes. This paper discusses research progress in understanding the effects of cobalt and some possible substitutes on microstructure, mechanical properties, and environmental resistance of turbine alloys.

INTRODUCTION

The United States is highly dependent on foreign sources for many materials required for its economic health. In the aerospace industry the four metals, cobalt, chromium, tantalum, and columbium have been identified as strategic materials. The United States imports in excess of 90 percent of each of these metals, and one country controls a major portion of the U.S. supply (ref. 1) for each metal. The National Materials and Minerals Policy, Research, and Development Act of 1980 (ref. 2) has helped to focus attention on this critical problem that faces not only the aerospace industry, but most other industries as well. Government agencies are responding to this Act by conducting research, holding public workshops and conferences, and coordinating efforts through various committees.

NASA Lewis Research Center has undertaken a long-range program in support of the aerospace industry aimed at reducing the need for strategic materials used in gas turbine engines (refs. 3 to 5). The program is called "COSAM - Conservation Of Strategic Aerospace Materials." This program has three general objectives; they are

(1) To contribute basic scientific understanding to the turbine engine "technology bank" so as to maintain our national security in possible times of constriction or interruption of our strategic material supply lines.

(2) To help reduce the dependence of United States military and civilian gas turbine engines on disruptive worldwide supply/price fluctuations in regard to strategic materials.

(3) To help minimize the acquisition costs as well as optimize performance of such engines so as to contribute to the United States position of preeminence in world gas turbine engine markets.

To achieve these objectives, the COSAM program is developing the basic understanding of the roles of strategic elements in today's nickel-base superalloys and will provide the technology base upon which their use in future aircraft engine alloys/components can be decreased. Technological thrusts in three major areas are underway to meet these objectives. These thrusts are strategic element substitution, advanced processing concepts, and alternate material identification. Based on criticality of need, initial efforts are concentrated on the strategic elements cobalt (97 percent imported), chromium (91 percent imported), tantalum (91 percent imported), and columbium (100 percent imported). This paper will focus on the major thrust of strategic element substitution and specifically on the roles of cobalt in commercial, nickel-base superalloys.

The strategic nature of cobalt in the U.S. arises not only because of the high import dependence, but also because of the location of the major sources, Zaire and Zambia in southern Africa, as illustrated in figure 1. The stability of the governments in these two countries is of major concern (ref. 6), and it was the invasion of Zaire in 1978 that led to the dramatic price increase and shortage of cobalt in the U.S. in 1978 through 1980. As a result of the price/supply situation for cobalt in 1978 through 1980, the United States has experienced a decline in cobalt usage (ref. 7). Figure 2 shows that 20 million pounds of cobalt were consumed in 1978, but by 1982 usage was down to an estimated 10.4 million pounds, a reduction of nearly 50 percent during the 4-year period. It should be pointed out that the stunted U.S. economy in 1981 and 1982 has undoubtedly contributed to this decline in cobalt usage. During this same period, the use of cobalt to produce superalloys, primarily nickel-base alloys for aircraft engines, increased from 4 million pounds in 1978 to a peak of 7.2 million pounds in 1980 before it declined to an estimated 3.8 million pounds in 1982. The decline in U.S. aerospace consumption of cobalt may be attributed in part to the economy, but concerted actions by the gas turbine engine manufacturers to reduce cobalt usage through efforts such as substitution and near net shape processing also have contributed to this downward trend.

Superalloys still remain the major user of cobalt within the U.S. economy as shown in figure 3. Of the 10.4 million pounds of cobalt consumed by the United States in 1982, 37 percent of it went for superalloy production used primarily for aircraft gas turbine engines (ref. 1). The dependence of gas turbine engines on the strategic material cobalt as well as the other strategic materials is illustrated in figure 4. The strategic metals cobalt, chromium, tantalum, and columbium are contained in superalloys, stainless steels, and steels that are used in engine manufacturing in such components as compressors, combustors, and turbines. The need for these metals has increased as the demands have grown for higher durability plus higher performance, fuel efficient aircraft turbine engines. For example, the strategic metal input requirement for an F100 turbofan engine is shown in figure 5 to be about 2500 pounds. Based on the essential nature of these metals and in order for the U.S. aircraft industry to maintain its competitive position, supplies must be readily available at a reasonably stable cost or conversely substitute material technology must be on the shelf which will allow engine manufacturers to use alternative materials in the event of a strategic material cutoff or price escalation such as occurred in 1978.

Because of the importance of cobalt to the aircraft engine industry several research programs were initiated as part of the COSAM program to determine the roles of cobalt in nickel-base superalloys which constitute the major use of cobalt in U.S. aircraft engines. A further objective of the programs was to identify less strategic substitutes for cobalt in a variety of nickel-base superalloys. Such research efforts could have long-term national benefits, and, in addition, the methodology developed in these programs could serve as a model for future efforts involving other strategic elements.

Three nickel-base superalloys were initially selected for the COSAM investigation on cobalt. The three alloys are listed in Table 1 with their typical applications in the aircraft engine industry, the forms in which they are used and remarks as to why they were selected for the COSAM activity. Applications include turbine disks as well as low- and high-pressure turbine blades. A variety of product forms are represented by the applications of the three alloys as noted in the table. The selection of the alloys was based primarily on the considerations given in this table. Waspaloy* was selected because it represented the highest tonnage of cobalt in commercial aircraft engines. Udimet*-700 was selected because it has a composition similar to many of the cobalt-containing nickel-base superalloys, and it is used in the as-cast, as-wrought ingot, as-wrought powder, and as-HIP powder metallurgy fabricated conditions. Thus, the composition versus processing study opportunities were great. The potential for determining the impact of cobalt on both conventionally cast and D.S. polycrystalline and single crystal turbine blades was the reason for selecting MAR-M*247. After initial evaluation of these three alloys, additional alloys Nimonic* 115 and Udimet 720 were added to the program to further illucidate the roles of cobalt in nickel-base superalloys.

The COSAM Program is constituted as a cooperative program involving NASA, universities and industry. Various research efforts are being conducted under the overall programmatic management of the NASA Lewis Research Center. Some of this work is being conducted in-house at Lewis. There are also cooperative projects under way involving Lewis with both industry and universities to optimize the expertise at each organization and to seek synergistic results from the combined efforts. This research cooperation is presented graphically in figure 6. Typical roles for each organization are shown. These roles, of course, vary from project to project. For example, one project can involve an industry contract or a university grant for the bulk of the effort with a range of supporting contributions from the other partners. Another project may be conducted mainly in-house at Lewis with a range of support from industry or a university. Universities involved in the cobalt substitution program include Columbia University, Purdue University, and Case Western Reserve University. Industry involvement on this program includes Special Metals Corporation, Battelle Columbus Laboratories, and IIT Research Institute.

RESULTS

Metallurgy

Central to the studies being performed under the COSAM Program are efforts to gain a basic understanding of the alloying effects of cobalt in nickel-base superalloys. A significant effort has therefore been directed toward studying the physical metallurgy of low cobalt derivatives of several commercial nickel-base superalloys. These studies will be reviewed here with regard to the γ - γ' relationships and other microconstituents.

<u>γ - γ' Relationships</u>. The effects of reducing cobalt content on liquidus, solidus and gamma prime solvus temperatures were determined for Udimet-700, Nimonic 115, Udimet 720, and MAR-M247 (refs. 8 to 11). The nominal alloy composition and γ' content of the alloys are listed in Table 2. As one might expect in systems with 4-7 components, no universal trends were observed. In these alloy systems, it was observed that reducing cobalt increased the γ' solvus temperature typically about 3° C per atom percent of cobalt. Jarrett et al., (ref. 8), have rationalized this behavior with findings of Heslop (ref. 12) and Mauer, et al., (ref. 13) in terms of a pseudo-binary phase diagram based on Heslop's work. Their diagram shown in figure 7 shows that at low levels of γ' formers (Al + Ti), reducing cobalt lowers the γ' solvus while at higher

*The trade names Waspaloy, Udimet, MAR-M, René and Nimonic are for United Technologies Corporation, Special Metals Corporation, Martin Marietta Corporation, General Electric Company, and the Inco family of companies, respectively.

levels, typical of modern superalloys, the behavior reverses. A cross-over point occurs at about 7 atomic percent Al + Ti, the composition of Waspaloy, where it is inferred that the γ' solvus temperature is independent of cobalt content.

Of interest for heat treating and working these alloys is the change in the solidus temperature as a function of cobalt content. For most compositions, reducing cobalt content appeared to raise the solidus temperatures, the exception being the small (5 wt. percent) cobalt content in the Udimet-700 alloy series (ref. 14), and in a single crystal derivative of MAR-M247 (ref. 11). The general trend however, is that while reducing cobalt increases the γ' solvus and solidus temperatures in higher γ' fraction alloys, the difference between the γ' solvus and solidus temperature decreases with removal of cobalt from the alloys.

In the alloys Waspaloy, Udimet-700, single crystal MAR-M247 and Nimonic 115 nickel substitution for cobalt had little effect on the amount of γ' formed. This would have been anticipated from the reported (ref. 15) average γ' partitioning ratio for cobalt of 0.37 (1.0 being equal partitioning to γ' and γ). For MAR-M247, however, decreasing cobalt decreases the amount of γ' (ref. 10). The independence of γ' content with cobalt level was previously reported (ref. 16) in the Russian literature for the cast alloy ZhS6K.

As one might expect, because the lattice parameter for face-centered-cubic cobalt is greater than nickel or Ni_3Al, as nickel is substituted for cobalt the lattice parameter for both γ and γ' phases tend to decrease. The lattice parameter of γ' in Waspaloy increased as cobalt content was reduced (ref. 13). However,the amount of γ-γ' mismatch tended to decrease for Waspaloy and increased for Udimet-700 with reducing cobalt content. It is thought that the effects on lattice parameter and mismatch result both directly from cobalt and indirectly from the influence that cobalt has on the relative solubility of the other elements in the γ and γ' phases.

Cobalt has been shown to affect the solubility of other alloying elements in nickel-base alloys by several investigators. Heslop (ref. 12) showed that 20 percent cobalt decreases solubility for titanium and aluminum in nickel - 20 percent chromium alloys. More recently in the COSAM Program, Jarrett et al. (ref. 8) and Nathal and Ebert (ref. 11) have shown that reducing cobalt also effects the relative solubilities of chromium and nickel in γ and γ' in Udimet-700 and MAR-M247. Similar results have also been reported by Maurer et al. (ref. 13) for Waspaloy.

Other microconstituents. The nickel-base superalloys normally contain significant amounts of intentionally added carbon and boron. Therefore in most compositions one finds a variety of carbide phases and borides. Further, after long time exposure, additional phases such as sigma, mu or terminal solid solution of the body-centered-cubic elements have been observed. The single crystal derivities of MAR-M247 studied in this program did not contain intentionally added carbon and boron - therefore their behavior is not included here.

Radavich and Engel (ref. 17) have reported that reducing cobalt in Udimet-700 has little effect on carbide mass, but causes the major carbide to change from TiC to chromium rich $M_{23}C_6$. The latter carbide further changes from a fine grain boundary morphology at intermediate cobalt levels to a massive morphology at 8.6 percent cobalt. A small decrease in the amount of M_3B_2 was also observed with decreasing cobalt amounts. After aging at 815° C for 1000 hours sigma phase was observed in compositions having 8.6 percent or more cobalt.

Nathal (ref. 10) observed that for MAR-M247 the weight fraction of carbide increased by 1 wt. percent and the morphology changed from discrete particles to a grain boundary film as the cobalt was reduced from 10 percent to 0 percent. The carbides were identified as MC types. Exposure to 982° C for 1000 hours caused the formation of M_6C needles, but no sigma or mu phases were observed at any cobalt level.

Observations by Radavich and Engle (ref. 17) for Nimonic 115 also showed a shift in carbide morphology with changing cobalt levels. At 10 percent cobalt the carbides are randomly distributed particles, while at 5 and 0 percent cobalt grain boundary films are observed in the as-rolled condition. They suggest that reducing cobalt decreases the solubility of the gamma for carbon and boron. A similar effect of cobalt on carbon solubility has been reported for MERL 76 (ref. 18).

Mechanical Properties

Of prime interest in the COSAM Program is the assessment of how much cobalt might be reduced from nickel-base superalloys, while still offering useful engineering alloys. The tensile, stress rupture and low cycle fatigue properties of low cobalt alloys will be discussed in this section. Readers are cautioned, however, the data were obtained from small heats and commercial size heats might result with differing properties.

Tensile properties. The room temperature tensile properties of cobalt modified Udimet-700 given either a partial or full γ' solution treatment are shown in figure 8 (ref. 8). The elevated temperature strength of cobalt modified MAR-M247 (ref. 19) are shown in figure 9. In all cases, it can be seen that cobalt has only little influence on the ultimate and yield strength of the alloys. Earlier work (ref. 16) by Lashko et al., also showed that additions of 10 percent cobalt changed the tensile and yield strength of ZhS6K only about 10 percent.

Stress-rupture life. The stress rupture behavior of Udimet-700 (ref. 14) was also studied in two heat treatment conditions. One heat treatment, typical of that which might be given to materials intended for low temperature service, for example disk applications, used a sub-solvus treatment, thus retaining a relatively fine grain size. The other treatment intended to maximize high temperature properties as required for blade applications, used a full γ' solution treatment. The stress rupture results are summarized in figure 10. For materials given partial γ' solution treatments, (fig. 10(a)) Harf's (ref. 20) results show that 0 percent cobalt and 17 percent cobalt alloys have about the same rupture life, with a maximum occurring at about 4 1/4 percent cobalt. Jarrett and Tien (ref. 14) however, show that the rupture life is independent of cobalt between 8 1/2 percent cobalt and 17 percent cobalt, but below 8 1/2 percent cobalt the stress rupture life decreases significantly. It can be seen that when the alloy is heat treated to fully solution the γ' (fig. 10(b)), that the stress rupture life at the low stress increases linearly with cobalt reduction in Udimet-700. This has been attributed by Jarrett et al., (ref. 8) to be due to formation of increasing amounts of fine γ' in the lower cobalt alloys. No explanation is offered for the behavior at the higher stress of 689 MPa where the life is independent of cobalt level.

If one examines the details of the heat treatments it is found that Harf used a partial solution temperatue about 40° C below the γ' solvus temperature for all of his alloys. Jarrett et al., on the other hand, used a partial solution temperature about 40° C below the γ' solvus between 8 1/2 and 17 percent cobalt, but used a constant temperature of 1129° C for the 0 to 8 1/2 percent cobalt alloys. That results in a solution temperature which is increasingly below the solvus for the alloys between 8 1/2 and 0 percent cobalt. At 40° C below the γ' solvus the amount of γ' changes about 1/4 percent (wt.) per degree C as the temperature changes (ref. 21). The γ' solvus increases at a rate of about 3° C per percent of cobalt removed. Thus one would expect that the 0 percent cobalt alloy studied by Jarrett et al., would contain about 6 percent less fine γ' than the 8 1/2 percent cobalt alloy. In fact they report 28.8 percent fine γ' in the 0 percent cobalt alloy compared to 34.2 percent for the 8 1/2 percent cobalt alloy or 5.4 percent less fine γ'. It seems that the loss in stress rupture life, with reduced cobalt observed by Jarrett et al., can be largely explained in terms of the reduced fine γ' available for strengthening.

Nathal et al., (ref. 19) reported decreased stress rupture life for reduced cobalt polycrystalline MAR-M247. This is shown in figure 11(a). They attributed the loss of rupture life to both reduced γ' amounts with decreasing cobalt levels and to the formation of a grain boundary carbide film at 0 percent cobalt. In contrast, Nathal and Ebert (ref. 11) reported an increase in rupture life with decreasing cobalt in stripped MAR-M247 single crystals as shown in figure 11(b). The absence of grain boundaries and hence carbide film formation may contribute to the reversal in behavior.

For the low γ' volume fraction alloy, Waspaloy, Maurer, et al. (ref. 13), reported decreasing stress rupture lives with decreasing cobalt levels. The slight decrease in the amount of γ' in the low cobalt alloys could not account for the loss of rupture life observed. They attributed part of the rupture life degredation to both a change in carbide partitioning at the grain boundaries and to increasing the stacking fault energy of the matrix with reducing cobalt content. Law, et al. (ref. 18), used similar reasoning to explain the reduced creep-rupture behavior of 0 percent cobalt MERL 76 and AF115 alloys.

Low cycle fatigue. Creep-fatigue tests were conducted on axially-loaded specimens of Waspaloy at 538° C and Udimet-700 at 760° C (refs. 22 and 23). Four different types of strain-controlled test cycles were performed on each composition of the reduced cobalt alloys. These cycles are listed below and the resultant stress-strain hysteresis loops are illustrated in figure 12:

- PP - High frequency, 0.5 Hz triangular wave form.
- CP - Same as PP, except with a 1-minute hold period at peak tensile strain.
- PC - Same as PP, except with a 1-minute hold period at peak compression strain.
- CC - Same as PP, except with a 1-minute hold period at both peak tensile and compression strains.

For direct comparison, the creep-fatigue test results were normalized by using a calculated life for an axial inelastic strain range of 0.0025 cm/cm, $N_f.0025$. The results of this analysis are shown in figure 13 for the two reduced cobalt content series of alloys. Examination of the Waspaloy data suggests that reducing the cobalt content of this alloy did not have an influence on fatigue life. The alloy with 0 percent cobalt exhibited fatigue lives equal to the standard 13 percent cobalt Waspaloy for most of the creep-fatigue cycles. Examination of the Udimet-700 data suggests that fatigue life is independent of cobalt content for PP and CP cycles. In contrast, the CC and PC cyles drastically reduced fatigue lives of the standard 17 percent cobalt Udimet-700 alloy while all the reduced cobalt content alloys exhibited longer lives for these two cycles. Based on these limited results, it is concluded that the reduction and/or removal of cobalt from Waspaloy and Udimet-700 is not detrimental to their short-time, creep-fatigue resistance.

Thermal fatigue. Effects of reducing cobalt content in Udimet-700 on thermal fatigue resistance were determined by fluidized bed testing (ref. 24). Triplicate test specimens of each alloy composition were heated by immersion in a hot bed for 3 minutes followed by immediate transfer to a cooler bed for an immersion time of 3 minutes. This

cycle was repeated until specimen failure occurred. Specimens were examined after each 500 cycles. Failure was taken as the average of the number of cycles at the last inspection without cracks and the number of cycles at the first inspection with a crack. In this investigation, the fluidized hot bed temperature was increased at various increments to obtain cracking. A history of the test conditions is given in figure 14 for the Udimet-700 test results. Thermal fatigue lives are plotted as averages of the three test bars for each composition. Udimet-700 was evaluated in both the bare and coated (NiCrAlY overlay) conditions. The thermal fatigue results shown in figure 14 indicate that the best life (both bare and coated) was for the 8.6 percent cobalt content alloy. Interestingly, for the 4.3 and 8.6 percent cobalt alloys, the coated thermal fatigue life was less than that achieved by the bare material. Based on these thermal fatigue results, it appears that for both alloys the optimum cobalt content is about 8 percent, or at levels substantially lower than the alloy specifications of 17 to 19 percent cobalt for Udimet-700.

ENVIRONMENTAL RESISTANCE

Cyclic oxidation. The three nickel-base alloys, Waspaloy, Udimet-700, and MAR-M247 were tested in cyclic oxidation over the temperature range 760° to 1150° C for 1-hour exposure cycles for total times ranging from 100 to 1000 hours (ref. 25). Specimens were weighed and the surface X-rayed periodically throughout the duration of the test. Typical specific weight change data at 1100° C are shown in figure 15 for the reduced cobalt Udimet-700 and MAR-M247 alloys which represent the extremes in oxidation resistance. Reduced cobalt Waspaloy alloys exhibited oxidation behavior similar to the Udimet-700 alloys. Based upon specific weight change data, removing cobalt from Udimet-700 and Waspaloy substantially improves oxidation resistance and slightly improves oxidation resistance of MAR-M247. To compare the oxidation resistance of these alloys over the entire temperature range an oxidation attack parameter K_a was used. This was accomplished by fitting the weight change - time data to:

$$\Delta w/A = K_1^{1/2} t^{1/2} - K_2 t \tag{1}$$

where $K_1^{1/2}$ represents an oxide growth constant and K_2 an oxide spalling constant. K_a is then defined as:

$$K_a = K_1^{1/2} + 10\ K_2 \tag{2}$$

This K_a valve has been shown to correlate well with measured thickness changes (ref. 26). Figure 16 summarizes the oxidation behavior for the three alloy systems. The attack parameter is plotted on a log scale versus the reciprocal of absolute temperature. Only the 13 percent and 0 percent cobalt alloy data are plotted for Waspaloy and the 17 percent and 0 percent cobalt alloy data are plotted for Udimet-700. Based on extensive testing history at NASA Lewis, K_a values can be qualitatively rated as shown in the figure. "Excellent" implies a low growth rate with minimal spalling while "catastrophic" implies the test specimen is almost totally oxidized and converted to massive spall. It should be noted that the higher temperatures represent substantially accelerated testing compared to the normal use temperature of these alloys. At temperatures above 900° C the 0 percent cobalt content alloys of Waspaloy and Udimet-700 are clearly more oxidation resistant than their counterparts with the nominal 13 percent and 17 percent cobalt alloys, respectively. Cobalt content does not appear to affect oxidation resistance of MAR-M247 although the reduced 5 percent cobalt level alloy was on the lower side (better oxidation resistance) of the data band shown in figure 16.

X-ray diffraction data suggest an explanation for the oxidation behavior of these reduced cobalt alloys. Figure 17 schematically summarizes this behavior. In the Waspaloy and Udimet-700 alloys with Cr/Al ratios |1 (on an atomic basis), Cr_2O_3/chromite spinels and NiO form. Formation of NiO leads to excessive spalling and catastrophic failure. The presence of cobalt in the alloy accelerates this oxide breakdown process for the Waspaloy and Udimet-700 alloy series. In contrast, the Cr/Al ratio is 1 for MAR-M247 and Al_2O_3 and aluminate spinels are the chief oxides formed. These slower growing oxides are less prone to the formation of NiO in the scale which leads to accelerated spalling. In addition, the cobalt content does not appear critical in MAR-M247 suggesting that cobalt removal does not degrade oxidation resistance.

Hot corrosion. Both uncoated and coated specimens of Udimet-700 and uncoated MAR-M247 were evaluated. Wedge shaped test bars and the Mach 0.5 burner rig are shown in figure 18. Specimens were tested for 300 cycles. Each cycle consisted of holding the samples at 900° C for 1 hour followed by 3 minutes out of the flame during which time the samples cooled to near ambient temperature while in an air stream. The burner rig used jet A-1 fuel and pre-heated (~ 230° C) air which was seeded with a sodium chloride solution air aspirated into the combustor. Sodium level was maintained at 0.5 ppm in terms of fuel plus air and the sulfur content of the fuel ranged from 0.05 to 0.07 percent during the duration of the test. Photographs of the uncoated reduced cobalt Udimet-700 and MAR-M247 are shown in figures 19 and 20 (ref. 27), respectively. Based on appearance and weight change, hot corrosion resistance improves as cobalt is reduced in the alloys.

Data are currently being analyzed to quantitatively describe these results. In contrast, an aluminide coating applied to the reduced cobalt content Udimet-700 alloys

indicated (fig. 21), that at 1100° C in a Mach 0.3 burner rig, optimum corrosion resistance was achieved at a concentration near 12.8 percent cobalt (ref. 28). These results along with the low-cycle thermal fatigue results where uncoated specimens gave better lives than coated specimens, suggest that coating composition must be tailored to the reduced cobalt nickel-base superalloys.

CONCLUSIONS

The COSAM Program, through the cooperative research efforts of NASA, industry, and academia, is providing insight into the roles of cobalt in today's advanced nickel-base superalloys. It is apparent that some generalities can be made as to the major effects of reducing cobalt in many of the alloys investigated in the COSAM Program and by others cited herein. For example, tensile properties and low-cycle fatigue resistance are essentially independent of cobalt content in the alloys investigated. Oxidation resistance and hot corrosion resistance have been shown to improve with decreasing cobalt content in the alloys normally used for high-temperature blades (Udimet-700 and MAR-M247). Stress rupture results gave mixed results with rupture lives both increasing and decreasing as cobalt was reduced in the alloys. These results could be related to the effects that reducing cobalt had on fine γ' content, carbide composition and morphology, and to stacking fault energy. In the case of Udimet-700, reduced rupture lives at cobalt contents of 4.3 and 0 percent were increased to values exceeding or equal to the standard 17 percent cobalt alloy by modifying the heat treatment for these low cobalt alloys. Thermal fatigue resistance and Mach 0.3 burner rig oxidation resistance of coated specimens indicated that best results were achieved in reduced cobalt content Udimet-700 alloys with 8.6 to 12.8 percent cobalt.

Based on the results obtained to date, it is concluded that a number of today's nickel-base superalloys used in gas turbine engines appear to contain more cobalt than is needed to meet engine requirements. Cutting the cobalt content in half appears to be readily feasible. The first generation of modified cobalt content alloys has been the result of substituting nickel for cobalt. Now that some insight has been gained as to microstructural and microchemistry changes that accompany mechanical and environmental resistant changes in the reduced cobalt alloys, alloying elements other than nickel may enhance the properties of low/no cobalt content nickel-base superalloys. Large scale heats of the reduced cobalt alloys will have to be produced and evaluated to assure reproducibility of findings to date on laboratory size heats.

The results from the COSAM Program are encouraging in that they hold the potential of reducing vulnerability of superalloys to cobalt in the event of future cobalt shortages or total cutoff of foreign supplies to the United States and other NATO nations.

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TABLE 1. SUPERALLOYS SELECTED FOR COBALT SUBSTITUTION STUDIES

Alloy	Typical engine application	Form	Remarks
Waspaloy	Turbine disk	Forged	Highest use wrought alloy in current engines
Udimet-700:	Turbine disk	Forged	Similar alloys used in various forms and applications
LC Astroloy	Turbine disk	As-hip-powder	
RENE 77	Turbine blades	Cast	
MAR-M247	Turbine blades and wheels	Cast	Conventionally-cast, D.S. and single crystal

TABLE 2. NOMINAL COMPOSITIONS AND γ' CONTENTS OF NICKEL-BASE SUPERALLOYS SELECTED FOR COSAM PROGRAM

	Weight percent												Percent γ'
	Ni	Co	Cr	Al	Ti	Mo	W	Ta	Hf	B	Zr	C	
Waspaloy	58	13.5	19.5	1.3	3.0	4.3	---	--	---	0.006	0.06	0.08	20
Udimet-700	53	18.5	15.0	4.3	3.5	5.2	---	---	---	.030	---	.08	45
MAR-M247:													
Polycrystalline	60	10.0	8.2	5.5	1.0	0.6	10.0	3.0	1.5	.020	.09	.16	55
Single crystal	62	10.0	8.2	4.4	1.0	0.6	10.0	3.0	---	---	---	---	63
Nimonic 115	59	14.0	14.6	4.9	4.0	3.5	---	---	---	.017	.001	.16	55
Udimet 720	55	14.7	18.0	2.5	5.0	3.1	1.24	---	---	.031	.031	.04	45

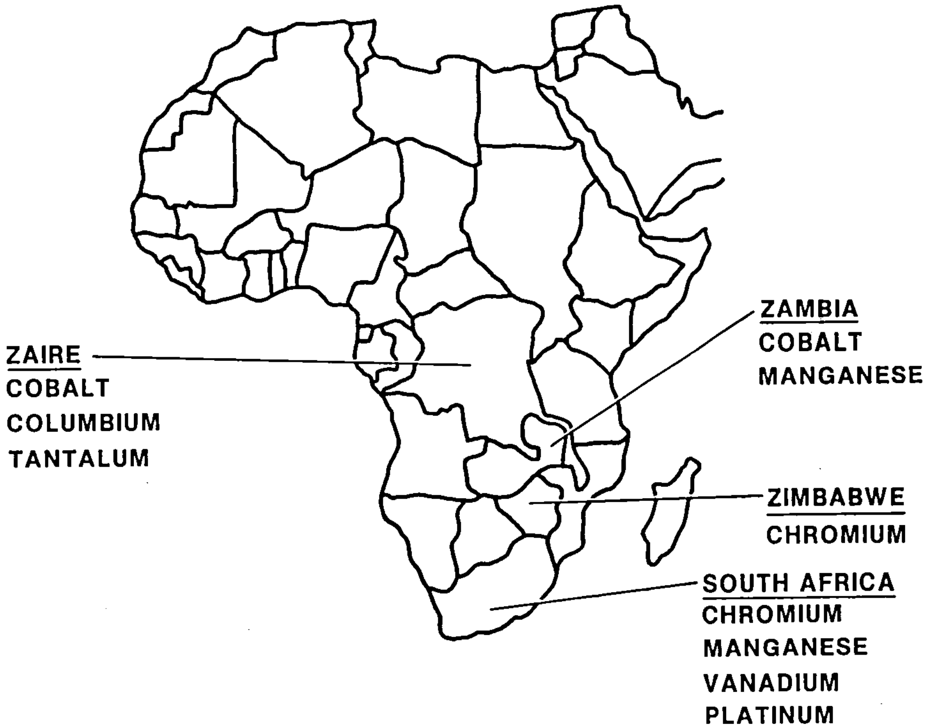


Figure 1. - Strategic material resources in Africa.

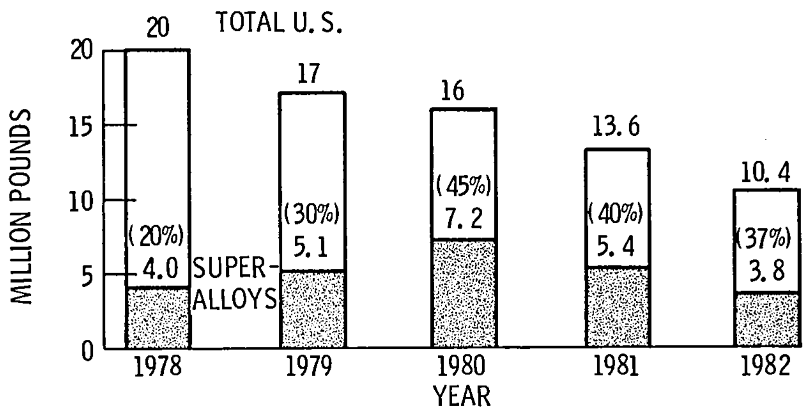


Figure 2. - Recent trends in United States and superalloy cobalt use.

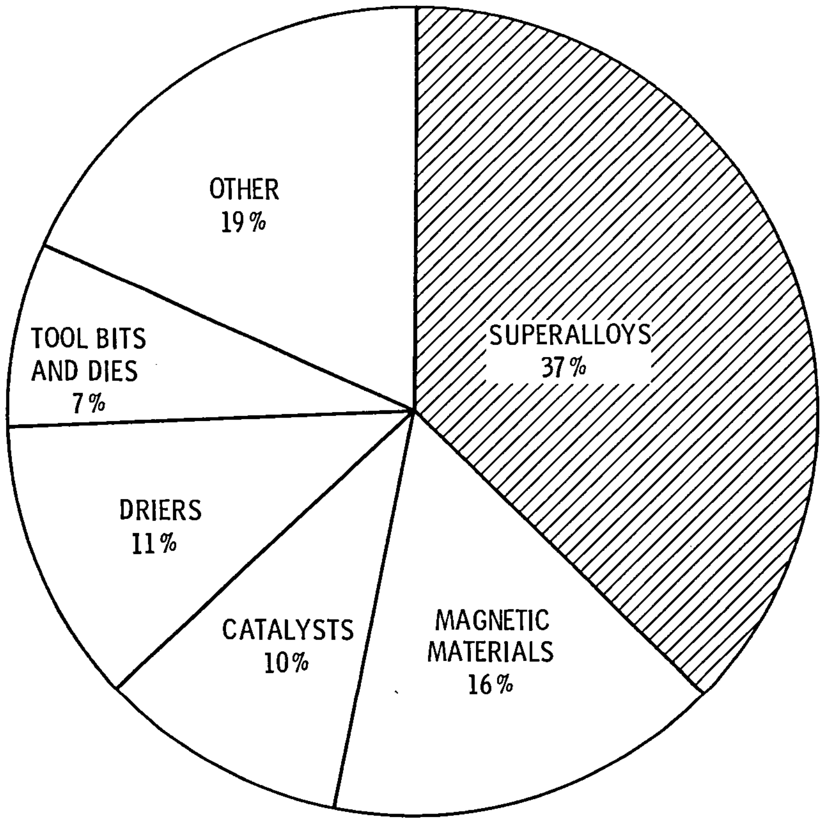
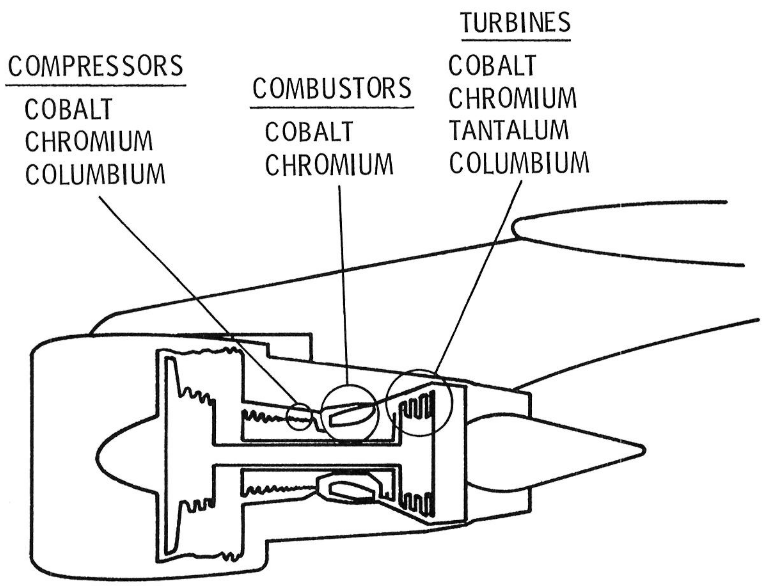


Figure 3. - Distribution of 1982 U. S. cobalt consumption-10. 4 million pounds.



NEEDED FOR PERFORMANCE AND LONG LIFE

COBALT - HIGH TEMPERATURE STRENGTHENER
CHROMIUM - CORROSION RESISTANCE
TANTALUM - OXIDATION RESISTANCE
COLUMBIUM - INTERMEDIATE TEMPERATURE STRENGTHENER

Figure 4. - Dependence of gas turbine engines on strategic materials.

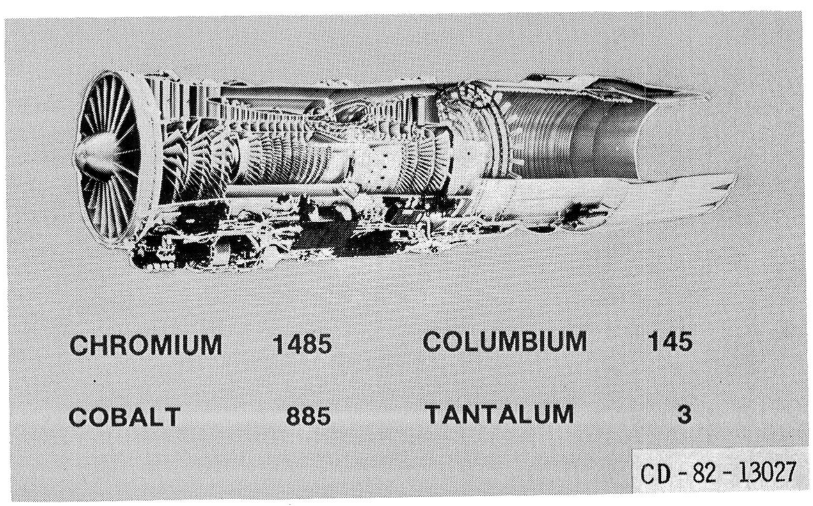


Figure 5. - F-100 engine input requirements in pounds.

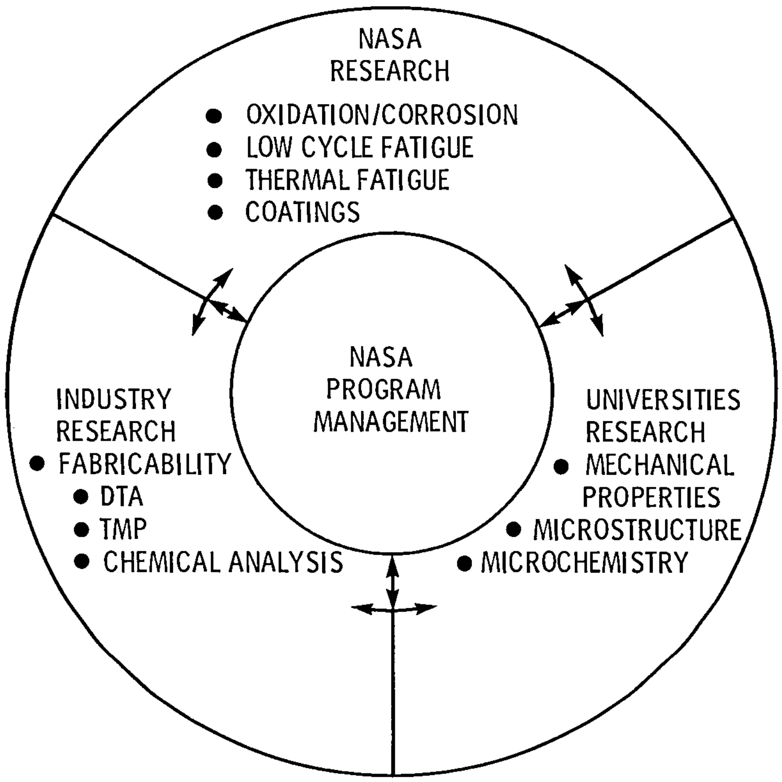


Figure 6. - Cooperative NASA-industry-university programs.

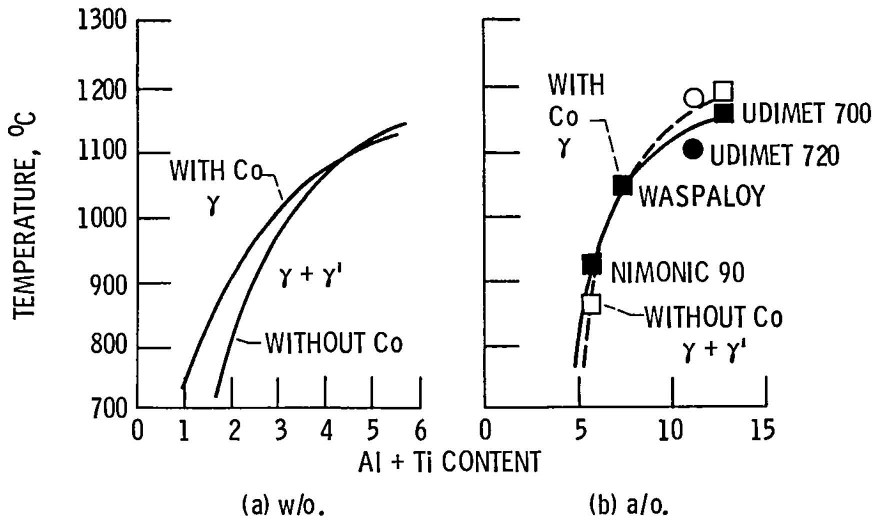


Figure 7. - Pseudo-binery phase diagrams after Heslop (ref. 12) for Ni-20 Cr and Ni-20Cr-20Co and after Jarret et al. (ref. 8) for commercial wrought alloys.

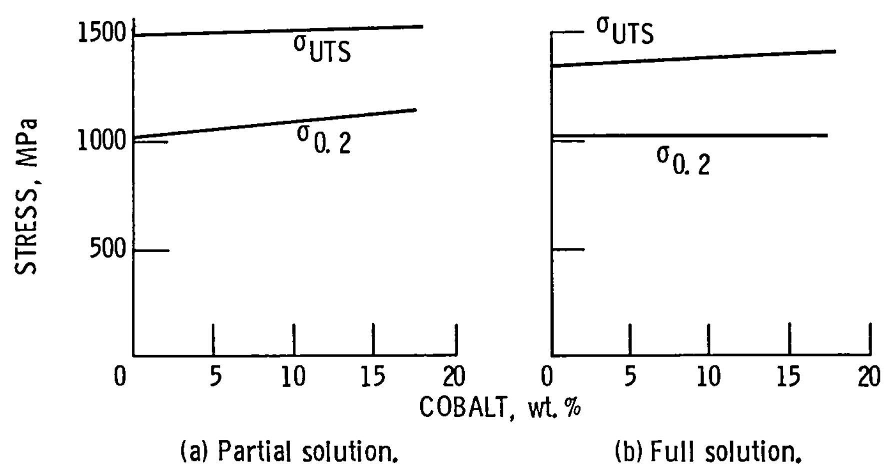


Figure 8. - Effect of cobalt on room temperature tensile strength of Udimet 700.

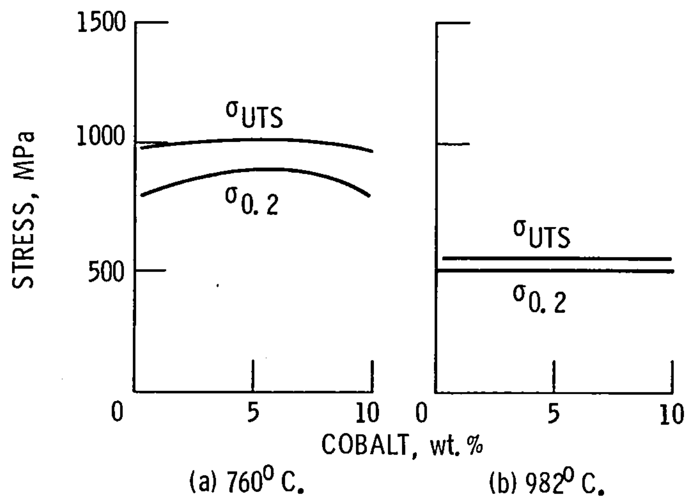


Figure 9. - Effect of cobalt on elevated temperature tensile strength of Mar-M 247.

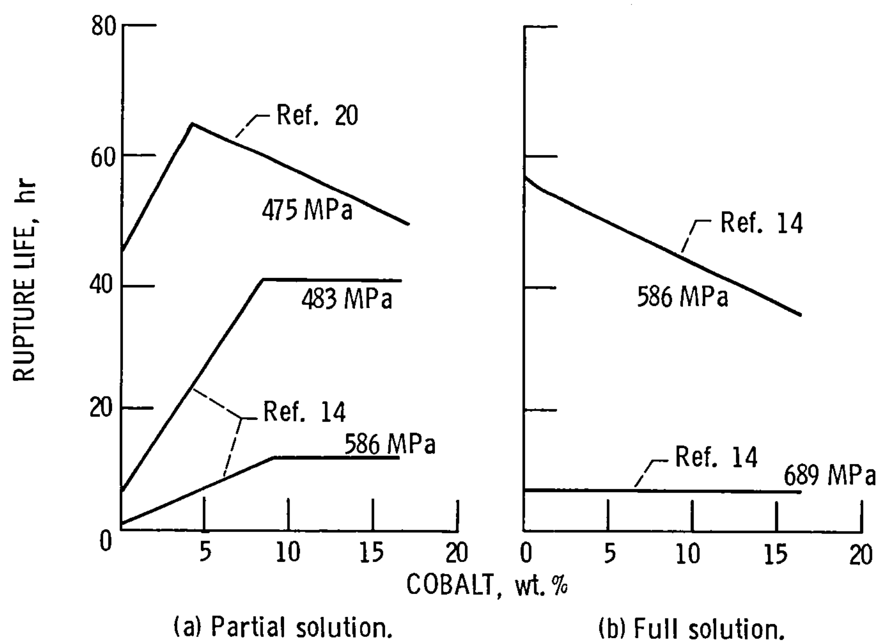
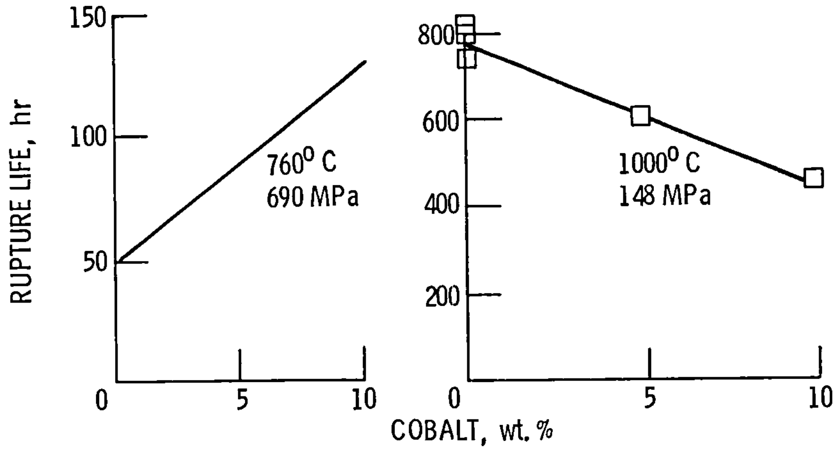


Figure 10. - Effect of cobalt on 760° C stress rupture life of Udimet 700.



(a) Mar M-247. (b) "Single Crystal" Mar-M 247.

Figure 11. - Effect of cobalt on stress rupture life.

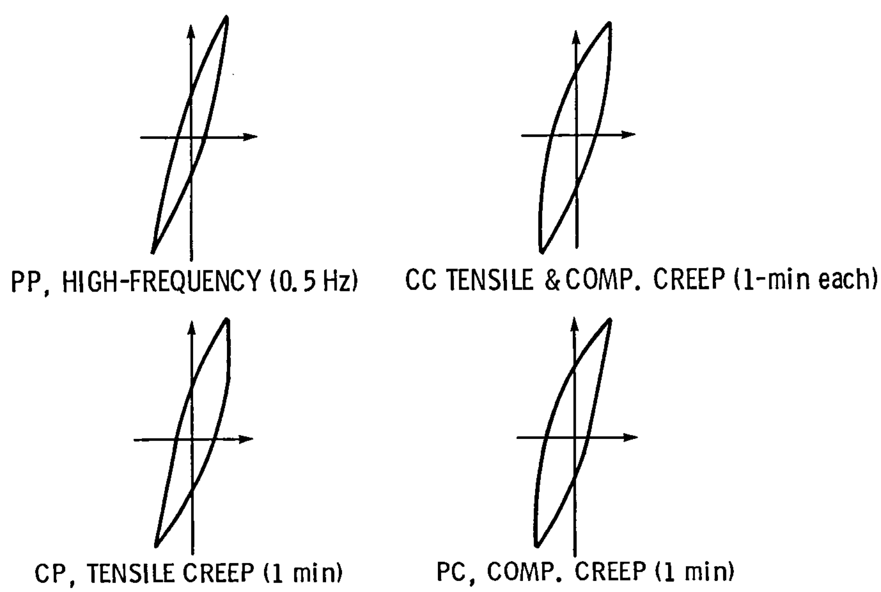


Figure 12. - Creep fatigue of low cobalt superalloys strain-controlled creep-fatigue cycles.

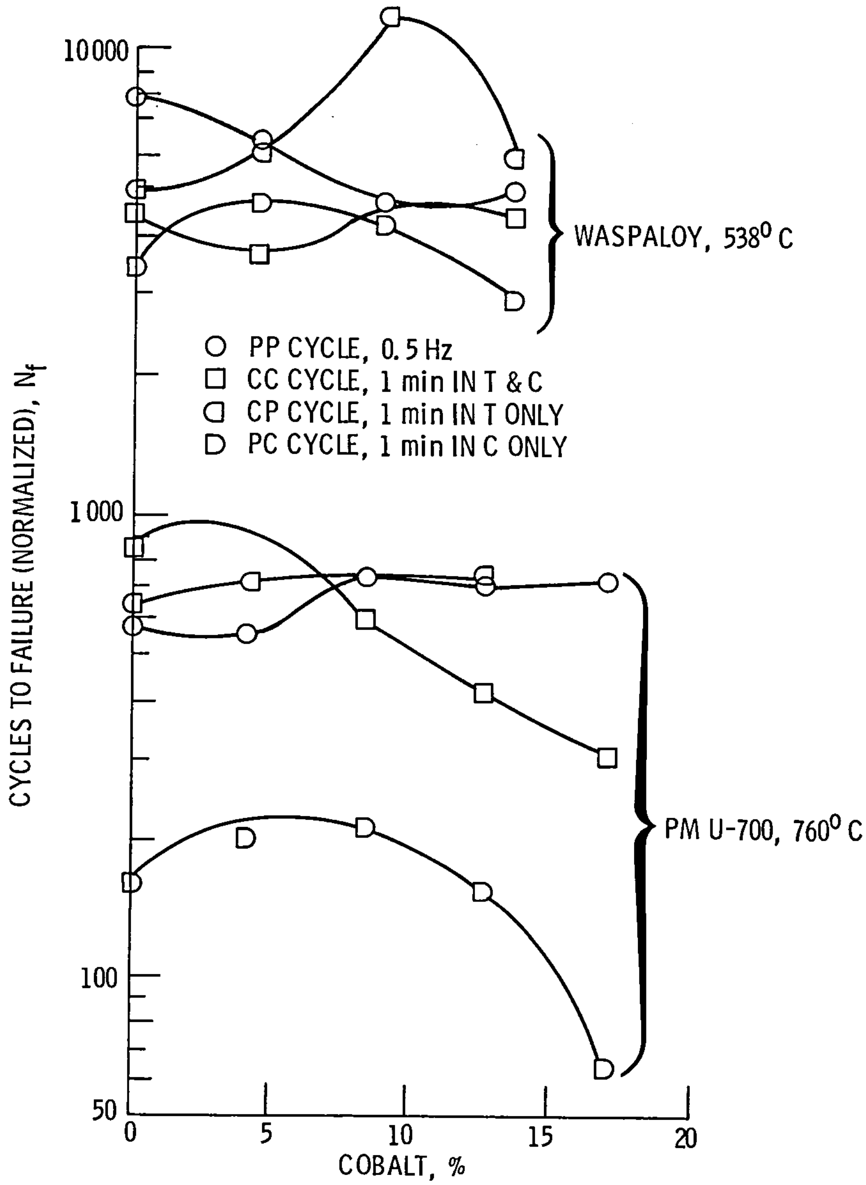


Figure 13. - Low-cycle, creep-fatigue response of Waspaloy and PM U-700. N_f normalized to axial inelastic strain range of 0.0025 cm/cm.

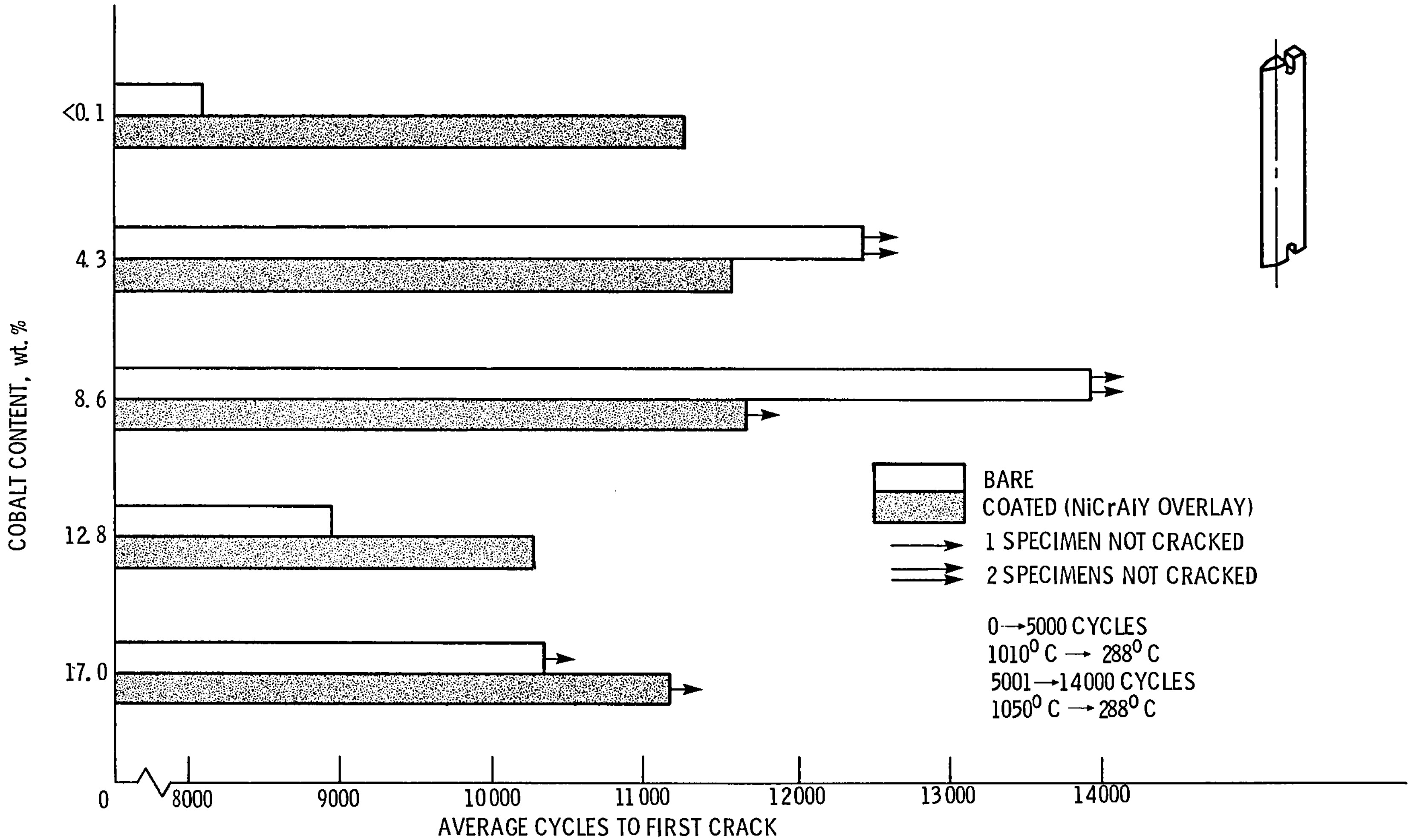
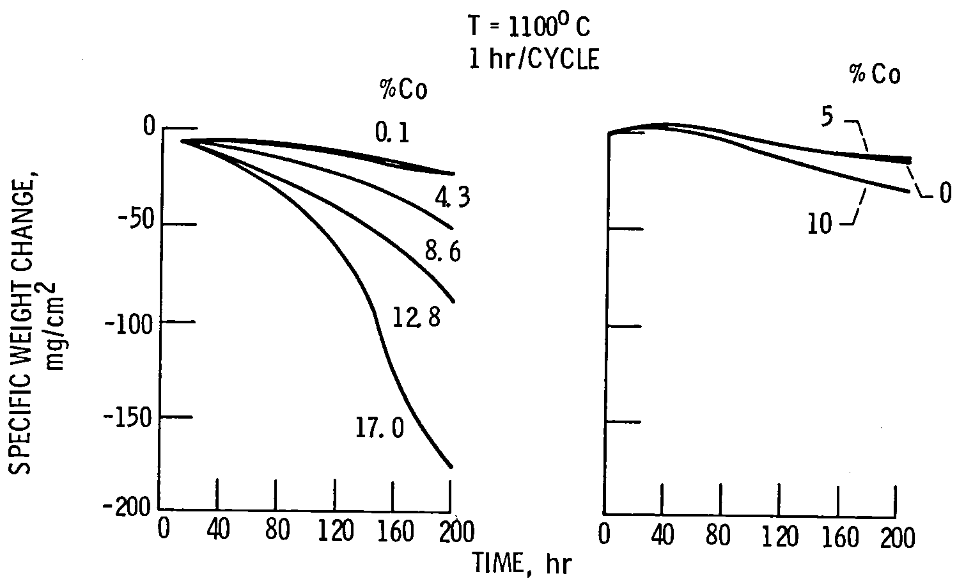


Figure 14. - Thermal fatigue resistance of reduced cobalt Udimet 700.



(a) Udimet 700.

(b) Mar-M 247.

Figure 15. - Cyclic oxidation behavior of reduced cobalt nickel-base superalloys.

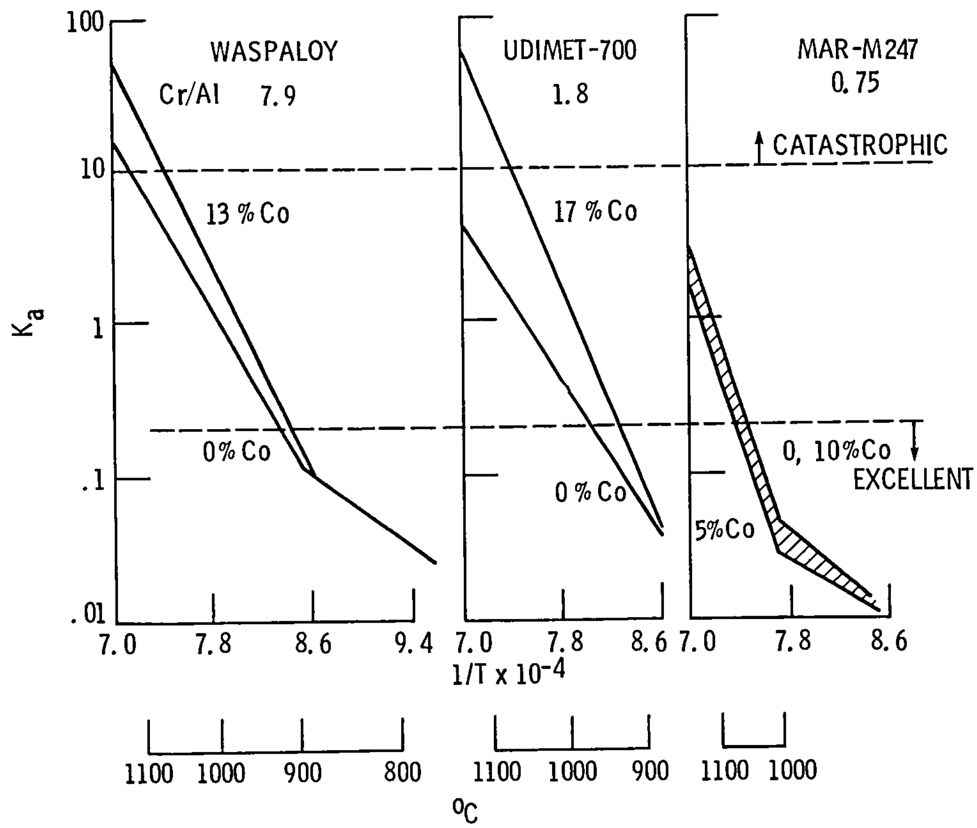


Figure 16. - Oxidation attack parameter, K_a, for reduced cobalt nickel-base superalloys.

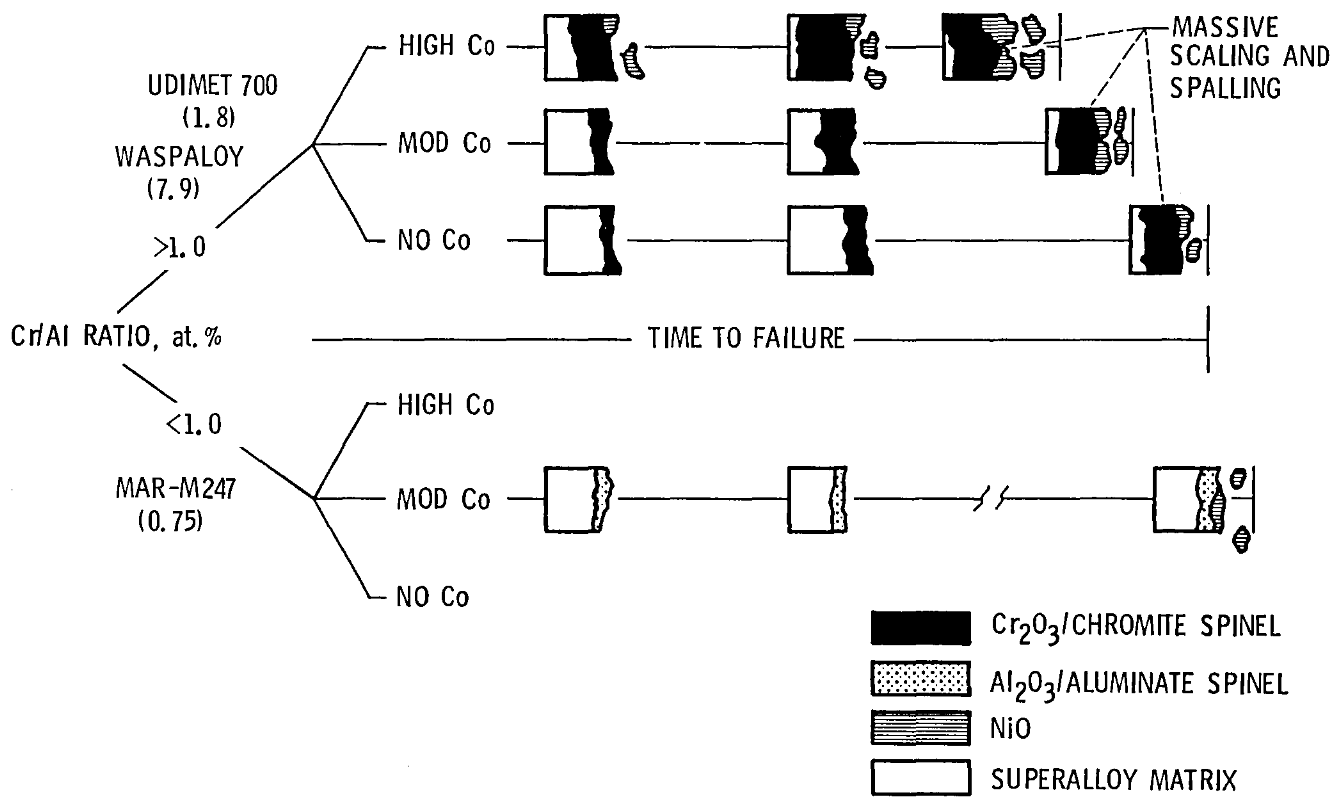
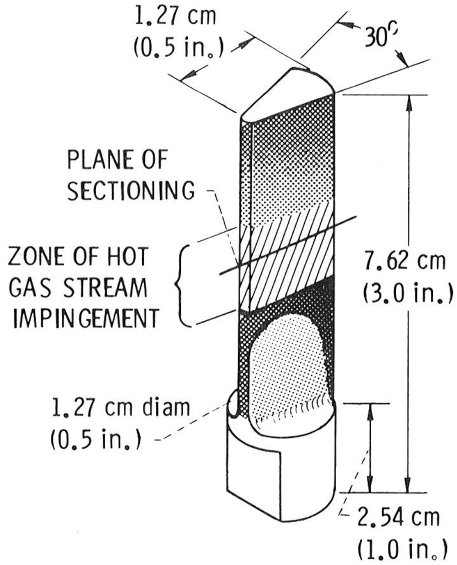
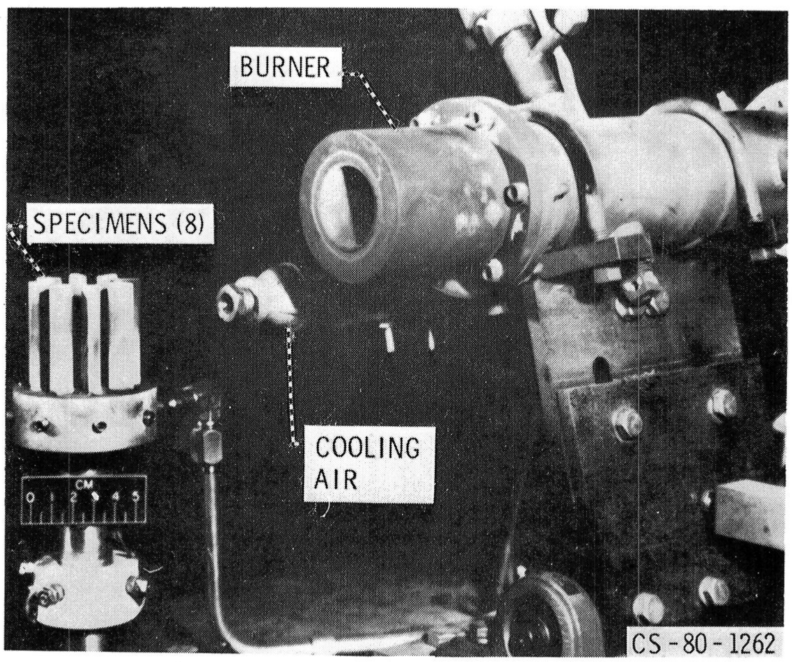


Figure 17. - Cobalt effect on nickel base alloy scaling protection and breakdown in cyclic oxidation.



Test bar.



Burner rig.

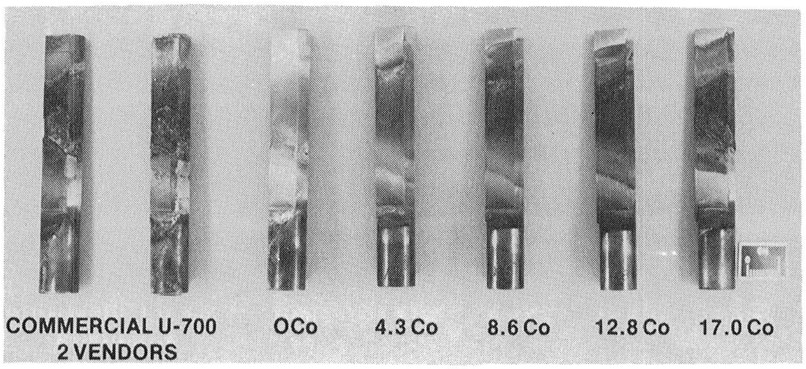
Figure 18. - Hot-corrosion apparatus and test specimen.

170 1-hr cycles

900^{0} C

0.5 ppm Na as NaCl

MACH 0.5



Modified U-700

Figure 19. - Effect of cobalt on hot corrosion.

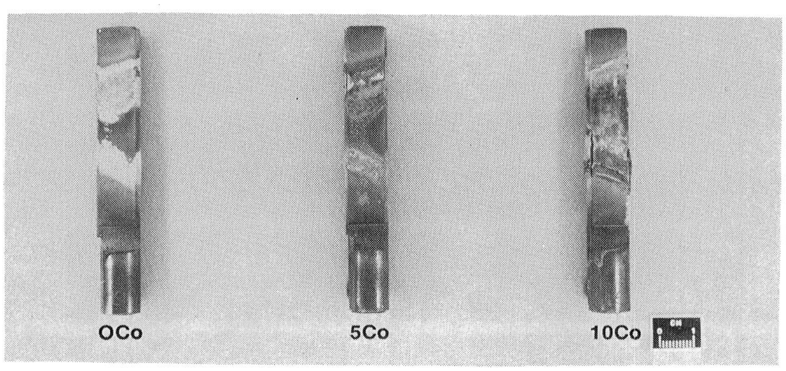
CD-82-12950

170 1-hr cycles

900^{0} C

0.5 ppm Na as NaCl

MACH 0.5



Modified MAR-M 247

Figure 20. - Effect of cobalt on hot corrosion.

CD-82-12951

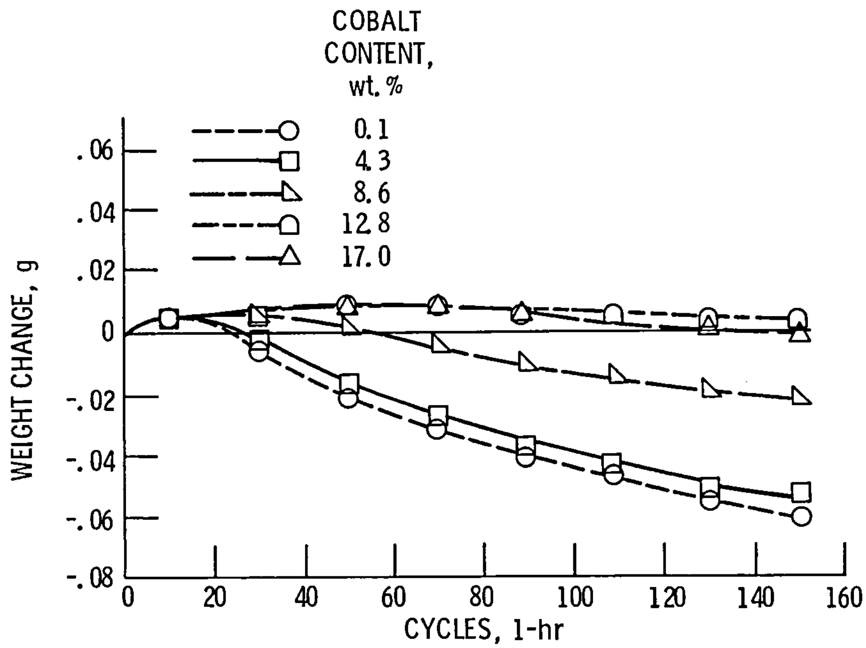


Figure 21. - Effect of cobalt on oxidation behavior of aluminized U-700 Mach 0.3 burner rig, 1100° C (front face).

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15. Supplementary Notes

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16. Abstract

The United States imports over 90% of its cobalt, chromium, columbium, and tantalum -- all key elements in high temperature nickel base superalloys for aircraft gas turbine disks and airfoils. NASA, through joint government/industry/university teams, has undertaken a long-range research program (COSAM - Conservation of Strategic Aerospace Materials) aimed at reducing or eliminating these strategic elements by examining their basic roles in superalloys and identifying viable substitutes. This paper discusses research progress in understanding the roles of cobalt and some possible substitutes effects on microstructure, mechanical properties, and environmental resistance of turbine alloys.

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